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Chapter 6

TRANSIENT-RADIATION EFFECTS ON ELECTRONICS (TREE) PHENOMENA [redacted]

[redacted] INTRODUCTION [redacted]

[redacted] This chapter introduces the subject of transient-radiation effects on electronics and provides a basic description of the interaction of nuclear radiation with matter as it applies to electronic components. The response of electronics to the radiation from a nuclear weapon burst depends not only on the radiation present at the electronics but also depends on the specific operating state of the electronics at the time of the radiation exposure and on the specific electronics in the system. A knowledge of the individual characteristics of the circuits contained in an electronics package, of the exact electronic components used in the circuits, and of the specific construction techniques and materials used in making the electronic components constitutes the necessary background for determining the radiation response of the electronic system. This chapter explains how the radiation interacts with different materials to produce a wide variety of effects. These material effects are used in the discussions of the component-part responses in Section VII of Chapter 9. Section IV of Chapter 14 contains a brief discussion of circuit and electronic-system response supplemented with discussions of general electrical responses of classes of systems (radios, radar, etc.).

[redacted] The cumbersome name applied to the class of effects that are the subject of this chapter, transient-radiation effects on electronics, is generally abbreviated to the acronym TREE. In general, TREE means those effects occurring in electronics as a result of the transient radiation from a nuclear weapon explosion or as a result of an environment designed to simulate that radiation. It should be understood that the transient-radiation from a nuclear explosion can be and is simulated by the use of controlled sources of steady-state and transient radiation since the environment produced can be correlated to the actual environment of interest, and thereby the effects on electronics can be studied.

[redacted] Although the weapons radiation environment lasts for a very short time, its effect on electronics can be both short or long term. For emphasis, it must be stated that the word transient in TREE modifies the word radiation and does not modify the word effects: the effects may be transient, semipermanent, or permanent.

[redacted] The term electronics means any one or all of the following: electronic component parts, electronic component parts assembled into a circuit, and circuits assembled into a system. TREE studies also may include the response of electromechanical components connected to the electronics, e.g., gyros, inertial instruments, etc. TREE does, however, specifically exclude other types of component parts or systems such as hydraulic cylinders and hydraulic systems, fuel lines and fuel systems, etc. This exclusion is made since electronics as a group or as part of a hybrid system are one of the most radiation-sensitive portions of a system.

[redacted] There are several points to be emphasized about TREE. The TREE interest is in the environment at the electronics produced by the

[redacted]

[redacted] ENVIRONMENT [redacted]

[redacted] In order to specify the hardness required of an electronic system, or to formulate an analysis or test program on which its hardness level will be established, it is necessary to describe the radiation environment to which the electronic systems may be exposed. Since the multitude of components of this environment leads to confusion in understanding the variety of mechanisms whereby a nuclear explosion can affect the operation of electronic systems, the primary outputs of a nuclear weapon and the mechanisms whereby secondary radiation are generated will be reviewed. In quantifying the environment to which the electronics are exposed, it is first necessary to treat the primary output of the nuclear explosion, then transport this radiation through the atmosphere and generate secondary radiations by interaction with the atmosphere. At this point, the radiation incident at the system of interest can be quantified. Since most of the electronics are enclosed by some structural material, there is the additional effect of transport through such shields, and it becomes necessary to describe the radiation field as it interacts with the affected part.

[redacted] This step-wise description of the radiation explains the variety of methods and units by which the radiation field is described. The weapon designer usually describes the output from the nuclear explosion-total energy output, total number of neutrons emitted, total gamma-ray energy, and reaction pulse shape. The person who formulates specifications for system design usually describes the radiation field as it impinges on the system, e.g., energy per unit area, neutron fluence, gamma exposure, pulse shape as affected by radiation transport through intervening material. Finally, the designer of the individual electronic piece-part or circuit is concerned with describing the radiation in units that are convenient for quantifying the radiation effect that he has to take into account, e.g., energy deposition per unit mass or volume, 1-MeV equivalent neutron fluence, gamma dose, radiation pulse shape at the device.

6-1 Weapon Output [redacted]

[redacted] The weapon radiation output and its interaction with the atmosphere will be summarized in succeeding paragraphs, together with the units in which these radiations are usually described. Following this summary, the individual radiation effects of concern will be discussed, and the appropriate methods of describing the radiation at the affected parts or circuits will be described for each type of effect.

[redacted] The majority of the energy released in a nuclear explosion heats the material of which the nuclear device was composed, to temperatures of tens and hundreds of millions of degrees. A smaller fraction (0.1 to 10%) escapes promptly in the form of fast neutrons and prompt gamma rays (see Chapters 4 and 5). The intense thermal source radiates most of its energy in the form of X-rays. If the explosion occurs in a vacuum, or, if the weapon is a "hot" X-ray device (see Section II, Chapter 4) that explodes in relatively thin atmosphere, these X-rays can produce important TREE effects. Depending upon the specific temperature of the source, the X-rays have energies varying from a few to a few hundred kilovolts. One method by which the energy spectrum from such a source is frequently described is by specifying the temperature of a black body which would emit a spectrum that approximates the observed X-ray spectrum (Chapter 4). It should be noted that even though the temperature is usually specified as a number in units of keV (kilo-electron-Volts), this unit describes a spectrum of photon energies extending significantly below and above the quoted number [redacted] DNA (b)(3 [redacted] initial nuclear radiation (i.e., that radiation emitted within 1 minute following the burst) which, in turn, consists of both prompt and delayed radiation. The weapon-burst radiations of interest are neutrons, gamma rays, X-rays, and to a much less extent, electrons. The effects of interest are both temporary and permanent even though the radiation persists only for a short time.

[redacted] Examples of system responses to TREE and their consequences are given below. These examples represent only a small sample and are not necessarily representative of present day problems.

Effect in System Due to Temporary Disturbances of the Electronics	Typical Consequence
Change in logic state in missile-borne guidance computer	Program jump or disturbance of key data causing mission failure
Spurious (ill-timed) fuzing signal	Warhead dudding or premature detonation
Excess currents in transistors and capacitors in servo control loop	Excessive steering maneuvers causing structural instability
Excess currents in memory write circuits	Writing erroneous data in memory, usually causing mission failure
Microcircuit latchup following ionization pulse	Functional disabling of microcircuit until power is cycled off and on

Effect in System Due to Permanent Degradation of the Electronics	Typical Consequence
Neutron-induced loss of gain in lower-frequency transistors	Loss of power supply regulation; decreased servo-loop gain
Delamination of semiconductor wire bonds due to thermomechanical shock	Functional failure of the affected device, usually leading to mission failure
Neutron-induced loss of gain in higher-frequency transistor structures	Decreased fan-out capability in computer logic
Metallization burnout due to excess ionization-induced currents	Functional failure of affected device, usually causing mission failure

[redacted] prompt radiations have been [redacted] from the nuclear explosion, a residue of hot and radioactive debris remains. Some of its energy continues to be irradiated as thermal energy in the ultra violet and visual regions of the spectrum. Subsequent radioactive decay of the debris produces lower intensity gamma rays as well as emitting high energy electrons. These electrons are particularly important for high altitude nuclear detonations, which may inject the electrons into orbits trapped by the earth's magnetic field. These electrons are of particular concern to space vehicles whose orbits intercept the earth's radiation belts, because continued exposure to the electrons can cause significant perma[redacted] degradation.

[redacted] If the explosion occurs within or near the atmosphere, the prompt radiations interact with the constituents of the atmosphere, producing secondary effects. The X-rays are absorbed most strongly and, depending upon altitude, the air is heated by the interaction to produce an intense thermal source and a blast wave in the air (Chapters 1 through 4). The gamma rays interact to produce secondary electrons. In concert with the earth's magnetic field and/or inhomogeneities, such as the surface of the earth, these electrons create a radiating electromagnetic pulse (EMP) (Chapter 7). The neutrons interact with the atmosphere to produce secondary gamma rays (Chapter 5).

6-2 Time Considerations [redacted]

[redacted] The general time frame for the arrival of the various radiation components at the electronics package is sometimes important. In general, for the purposes of electronic vulnerability, the prompt gamma radiation can be considered as a single pulse. Since the flight time for X-rays and gamma rays of all energies equals the speed of light, *unscattered* photons arrive at the equipment with the same time distribution they had at the source, with a time delay of 3.33 μsec/km from the weapon burst. The arrival of the gamma pulse approximately coincides with the unscattered prompt X-rays.

[redacted] The neutrons arrive after the initiation [redacted] gamma- and X-radiation. Their arrival time depends on the neutron energy and the range to the receiver. The first neutrons to arrive will be the unscattered 14-MeV neutrons. Their time of flight is 19.3 μsec/km, therefore, they will arrive 16 μsec/km after photon arrival. The photons resulting from neutron inelastic-scattering (Chapter 5) will also begin to arrive at about this time. Within 32.8 μsec/km (the arrival time after photon arrival for 4-MeV neutrons), the photons resulting from neutron inelastic-scattering will be completed, since the inelastic-scatter contribution is negligible for lower energy neutrons. Within 69.0 μsec/km, the bulk of the unscattered 1-MeV neutrons will have been deposited. The photons resulting from neutron capture (or thermalization) typically will peak shortly after the arrival of the 1-MeV neutrons depending on the system configuration being studied. Both the thermalization time and the capture time following thermalization depend strongly on the interacting materials and the system configuration. The radiation of interest to TREE is complete in less than 1 minute.

6-3 Description of Radiation Fields [redacted]

[redacted] A complete description of the radiation [redacted] produced at the system should include the time dependence, angular distribution, and energy spectrum of each of the components. Of course, this should be done for a wide variety of conditions to cover all possible interaction scenarios. In practice, it is not necessary to be so thorough, and the following approximations are usually made:

- A worst case radiation environment is spe-

[redacted] cified and the objective is to have the system tolerate all combinations of environments that are less stringent than the specification.

- The incident radiation is assumed to be unidirectional. This is usually the worst case angular distribution, and it represents a reasonable approximation to reality.
- Where possible, the individual radiation fields are specified in units that facilitate conversion to those units that are convenient for describing the effect.

[redacted] For example, it is possible to specify the time dependent neutron energy spectrum incident on the system. Since the time dependence of arrival of unscattered neutrons is correlated with neutron energy, as discussed above, specifying the neutron energy spectrum, and the range of distances between nuclear explosion and the irradiated system, also is equivalent to specifying the time dependence. Finally, if the only effect of interest is permanent neutron-induced displacement effects, the spectrum can be replaced by a single quantity such as the 1-MeV damage equivalent neutron fluence. The meaning of these units and the method of calculating them will be discussed in following paragraphs. It must be emphasized, however, that such convenient units are intended for simplification only. They are useful only if the assumptions underlying their use are valid. In the foregoing example, specifying only the 1-MeV damage equivalent neutron fluence is useless for determining the magnitude of neutron-induced ionization effects quantitatively.

[redacted] The degree to which such simplifications can be used depends in large measure upon the simplicity of the interaction of the incident radiation with the target materials. A particularly simple case is the description of the gamma-ray environment. High energy gamma rays suffer negligible attenuation in passing through significant quantities of material, and they interact with matter to produce approximately the same energy deposition, independent of atomic composition of the target. Therefore, it has been possible to describe the gamma ray environment fairly simply and this has frequently led to carelessness. A more complicated situation, in which carelessness cannot be tolerated, is represented by the X-ray interactions. X-rays of energies of tens to a few hundred kilovolts are attenuated significantly even by thin missile skins and electronic subsystem boxes, and the energy deposition produced by such X-rays is a strong function of the atomic number of the target material. For this reason, it is invariably necessary to specify not only the total X-ray energy fluence incident on the system (usually given in calories/cm^2), its pulse width (usually given in nanoseconds), but also a range of possible energy spectra (sometimes given as explicit spectra, and at other times specified by a range of characteristic black body temperatures). The relating of such an exposure to the intensity of the radiation present at the affected area, such as the junction region of a transistor, requires detailed and specific calculations of the transport of the spectrum through the intervening material and the resultant energy deposition in the affected volume.

[redacted] The transport of the various radiation components to the site of the equipment of interest is discussed in Chapters 4 and 5. It is of value, however, to note that typical electronic packaging materials will not produce significant attenuation of the neutron and gamma ray components of the environment. They do represent significant shields of X-rays, particularly if high-Z materials are used for electronic envelopes. Only the higher energy photons penetrate to the electronics of interest. Since the lower energy photons produce the highest energy deposition per unit volume when they interact, such shielding is especially useful because it removes preferentially that portion of the photon energy spectrum that would be most damaging if it were [redacted] allowed to penetrate to the sensitive devices. This fact reinforces the observation that is necessary to specify both the X-ray energy fluence and its spectrum outside and inside the shield. Indicating only the energy-fluence attenuation factor of a shield would ignore the fact that remaining photons are less effective in producing damage.

[redacted] INTERACTIONS BASIC TO TREE [redacted]

6-4 Ionization [redacted]

[redacted] Ionization is that process by which electrons are freed from their parent atoms in a material. A free electron carries a negative charge. After losing an electron, the atom (then called an ion) carries a net positive charge. Thus, the process of ionization results in the formation of electron-ion pairs in a material. If none of the electrons or ions leave the material, the material remains electrically neutral, since the positive and negative charges balance one another. Nevertheless, characteristics of the material may be altered considerably by ionization. The number of electron-ion pairs formed and their subsequent behavior are of prime interest in determining the effects of ionization.

[redacted] Gamma rays interact with matter in three ways. The first is called the Compton effect. In this type of interaction, a gamma ray (primary photon) collides with an electron, and some of its energy is transferred to the electron (see Figure 6-1a). A secondary photon, with less energy, is created and departs in a direction at an angle to the direction of motion of the primary photon. The second type of interaction of gamma rays with matter is the photoelectric effect (see Figure 6-1b). A gamma ray, with energy somewhat greater than the binding energy of an electron in an atom, transfers all its energy to the electron, which is consequently ejected from the atom. Since the photon involved in the photoelectric effect transfers all of its energy, it ceases to exist and is said to be absorbed. The third type of interaction is pair production (see Figure 6-1c). When a gamma ray photon with energy in excess of 1.02 MeV passes near the nucleus of an atom, the photon may be converted into matter with the formation of a pair of electrons, equally but oppositely charged. The positive electron soon annihilates with a negative electron to form two photons, each having an energy of at least 0.51 MeV. In some cases, if the interaction takes place near the nucleus of a heavy atom, only one photon of about 1.02 MeV energy may be created.

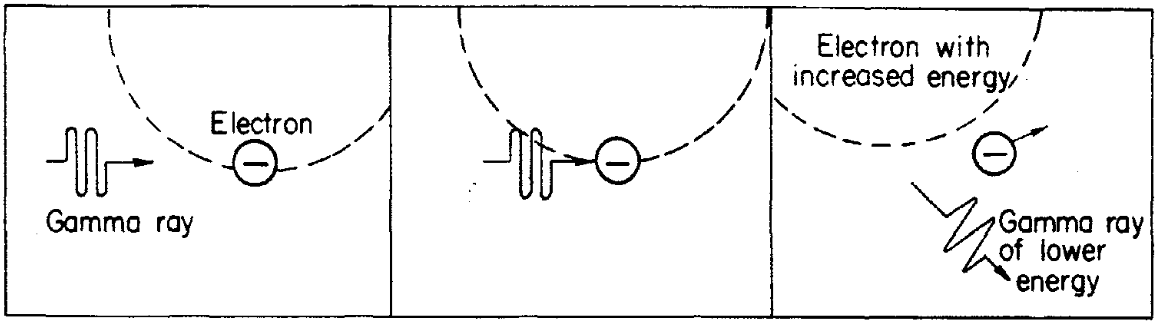
[redacted] Any photon (e.g., an X-ray or a gamma ray) can produce ionization in a material by these processes of creating secondary electrons that deposit their kinetic energy by ionizing the medium in which they are created. The relative importance or frequency with which each process occurs depends upon the photon energy and the characteristics of the material. The Compton process is the dominant ionization mechanism for most gamma rays of interest, particularly in electronic materials such as silicon, of which many solid-state devices are fabricated.

[redacted] Fast neutrons can produce ionization indirectly. As neutrons undergo inelastic scattering and capture in a material (see Section I, Chapter 5), gamma rays that are emitted can cause ionization. In addition, collision of a neutron with an atom may impart sufficient energy to the atom for it to cause ionization. Only high-energy neutrons ($E > 1$ MeV) contribute significantly to ionization. The 14-MeV neutrons arising from fusion reactions in a weapon are particularly important.

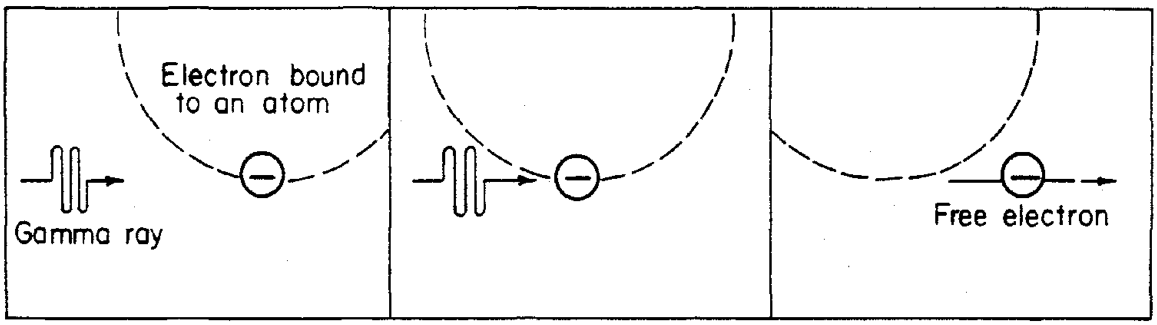
[redacted] The types of radiation that cause ionization in materials – namely, gamma rays, electrons, X-rays, and, to a lesser extent, fast neutrons – are known collectively as ionizing radiation.

[redacted] Once created by the ionization processes (either primary or secondary), the charged par-

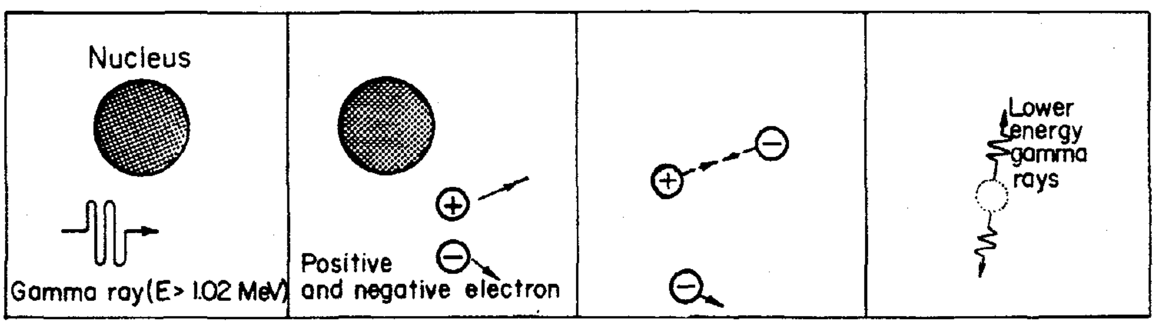
[redacted]



a. Compton Effect



b. Photoelectric Effect



c. Pair Production

Figure 6-1. [redacted] Gamma Ray Interaction with Matter [redacted]

[redacted]

[redacted]

[redacted] ticles (electrons or ions) are free to move in a material, scattering frequently and following a random-walk pattern. If the concentration of electric charge carriers throughout the material is not uniform, and if no externally applied electric field is present, the carriers will move from regions of high concentration to regions of low concentration. This movement is known as diffusion and it would be superimposed on the normal random-movement. If an electric field is present (e.g., as a result of an intentionally applied voltage), the carriers drift in the electric field while they undergo a predominantly random scattering. If impurities are present in the material (as they always are in solid-state devices, such as transistors and diodes), carriers may be captured (trapped) and immobilized by impurity atoms (traps). Eventually, the trapped carriers will be annihilated by their mates (oppositely-charged carriers) in a process called recombination. The net result of these processes is that the carriers diffuse and/or drift until they are trapped and usually recombined.

6-5 Displacement [redacted]

[redacted] As described above, ionization involves the movement of electrically charged electrons and ions in a material. Displacement involves the movement of atoms (which are electrically neutral)[redacted]

[redacted] Any material may be described as being either crystalline or amorphous. The atoms of a crystalline material (a crystal) are arranged in a definite, repeated, three-dimensional pattern called a lattice; the atoms of an amorphous material have no definite arrangement. Displacement is an important phenomenon in crystalline materials, and it is a very important phenomenon in TREE because many electronic devices (e.g., transistors, diodes, integrated circuits) are constructed from crystalline semiconductors – primarily silicon and germanium. Lattice defects result from the displacement of atoms from their usual sites in crystal lattices. The simplest lattice defects are extra atoms inserted between lattice positions (interstitials) and unoccupied lattice positions (vacancies). At least part of the resultant damage to the material is stable and accounts for permanent property changes of irradiated crystalline materials.

[redacted] The production of displacement damage in a crystalline solid is a complex process. An abbreviated history of this process follows.

(1) Radiation of an appropriate form enters the material, interacts with a lattice atom, and imparts to it a certain energy.

(2) The target (recoil) atom leaves its lattice site, thus creating a vacancy, and collides with other lattice atoms (see Figure 6-2).

(3) Other atoms are displaced from their sites, creating more vacancies.

(4) Eventually, most recoil atoms come to rest in interstitial positions, while a few fall into vacancies. Some of the interstitials and vacancies may be isolated, but most of them will be associated with other defects in cluster formations.

(5) The simple defects and defect clusters migrate through the crystal.

(6) Eventually, the mobile defects are annihilated by recombination of vacancy-interstitial pairs, are immobilized by the formation of stable defect clusters with other impurities of lattice defects (either present in the original material or created by the irradiation), or escape to a free surface.

(7) Meanwhile, the physical properties of the material are changed by the presence of the defects.

[redacted] Fast neutrons are very effective in producing displacement damage. Energetic electrons can also produce displacement damage; however, their displacement effects are negligible compared to those of fast neutrons.

[redacted]

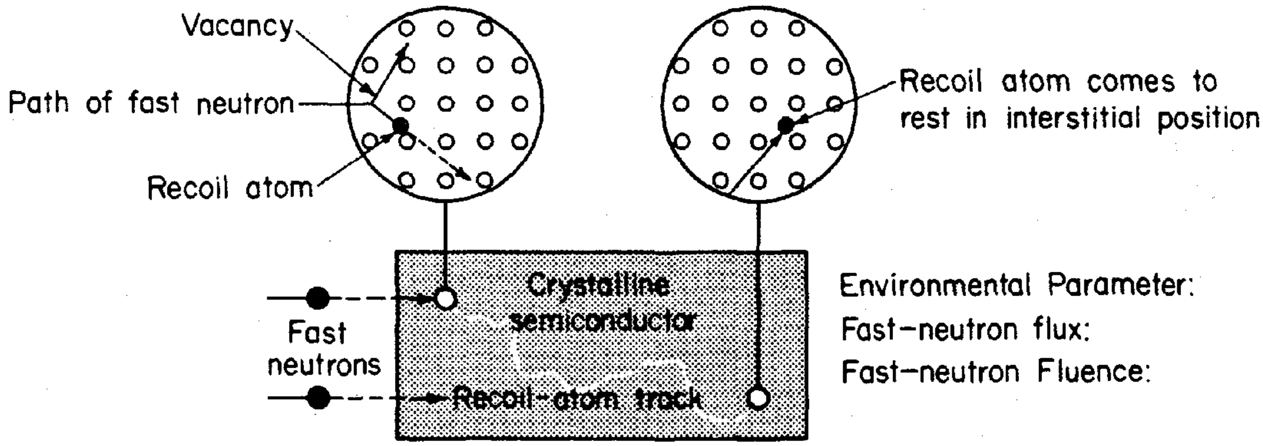


Figure 6-2. [redacted] Displacement Damage in a Crystalline Solid [redacted]

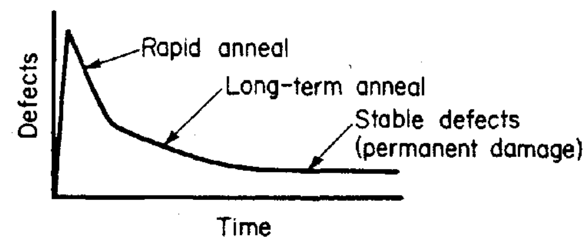
[redacted] The absolute magnitude of damage in a material caused by neutrons is difficult to predict because some of the defects that are produced will effectively disappear at room temperature, that is, anneal. However, much useful information can be gained from the relative value of the concentration of defects produced before annealing. Assuming the same fraction anneals, the relative concentration of stable defects would be in the same ratio. It has been found that the number of unannealed defects that are generated depends on the energy of the impinging neutron. The number of unannealed defects generated by a 14-MeV neutron (one from a fusion weapon) is about 2.5 times the number of unannealed defects generated by a 1-MeV neutron (roughly the average energy for a neutron from a fission weapon). As will be discussed below, the number of defects generated in semiconductor materials is directly related to the change in semiconductor device parameters.

[redacted] Not all of the defects produced in the displacement process are stable. Some defects are annihilated by recombination of vacancy-interstitial pairs, some combine with pre-existing lattice defects, and some eventually escape to a free surface of the material. The stable defects contribute to the permanent damage of the material. The unstable defects are said to disappear, or anneal, with time. In practice, this means that the degree of displacement damage in a crystalline semiconductor varies with time, reaching a peak rapidly and then partially annealing with time. The temperature of the material exerts a considerable influence on the amount of annealing that takes place. More annealing is observed at elevated temperatures.

[redacted] Annealing may be divided roughly into two time frames. Rapid, or short term, annealing occurs in times of the order of hundredths of a second. Long term annealing continues at a slower rate for times of the order of tens of seconds (see Figure 6-3). If the temperature remains constant, annealing will be essentially complete after one-half hour. The ratio of the damage observed at early times (number of defects present) to the damage after a very long time is called the annealing factor, which is a function of the time of measurement and other parameters. The maximum damage created at short times following the fast-neutron burst frequently is important to electron-system perfor-

[redacted]

mance. Therefore, the maximum annealing factor is an important quantity, because it indicates the peak damage that must be tolerated above the permanent damage in the steady state. Values of the annealing factor depend on the temperature and on the electrical condition of the material. An annealing factor of three is commonly used for room temperature at ~10 msec. Larger factors have been observed at shorter times, or low injection conditions (e.g., cut-off transistors).



Environmental Parameters:
Fast-neutron flux:
Fast-neutron Fluence:

Figure 6-3. [redacted] Annealing Due to Vacancy-Interstitial Recombination and Escape of Defects from Semiconductor [redacted]

6-6 Heating [redacted]

[redacted] Whenever a material absorbs energy from its surroundings and cannot instantaneously dissipate that energy, the temperature of the material will rise, i.e., the material will be heated. The temperature will return to ambient at a rate determined by the efficiency with which the material can dissipate heat to its surroundings. If the energy deposition is great, and the mechanisms for heat dissipation are inadequate, the temperature rise will be significant and will persist for a considerable time (see Figure 6-4).

[redacted] X-rays are the primary contributors to heating. Therefore, the relevant environmental parameters are the X-ray dose rate, and the X-ray dose. Predictions of the X-ray environment from nuclear weapon bursts and the X-ray absorption mechanisms are discussed in Chapter 4. Responses of electronic components to heating are discussed in Section VII, Chapter 9.

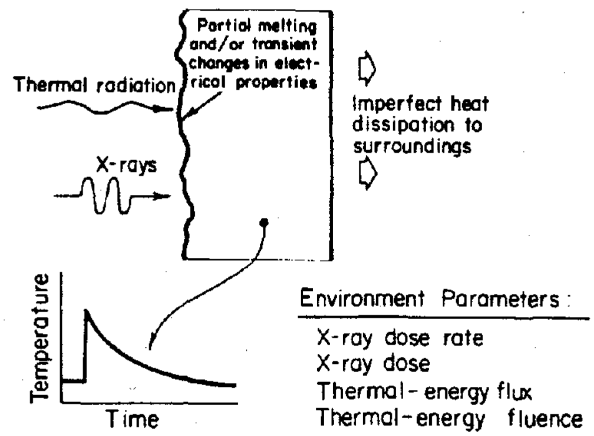


Figure 6-4. [redacted] Heating [redacted]

[redacted] MANIFESTATIONS OF TREE IN MATERIALS [redacted]

6-7 Ionization Effects [redacted]

[redacted] The important manifestations of ionization include (1) charge transfers, (2) bulk-conductivity increases, (3) excess minority-carrier generation, (4) charge trapping, and (5) chemical effects.

[redacted] Charge transfer results from the escape of some electrons produced during ionization from the surface of the material being ionized. If the net flow of electrons is out of the material, the material will be left with a net positive charge. If these electrons are stopped in an adjacent material, a transfer of charge will have occurred from one material to the other, and a difference of potential (or voltage) will exist between the two materials.

[redacted] The transfer of charge from one material to another can have a number of effects. The most obvious one is that a current will flow through any electrical circuit connecting the two materials to restore charge neutrality. The charge will produce electric and magnetic fields during transit. If there is matter in the gap between the materials, the charge transfer also will produce ionization and conduction in response to local electrical fields. Finally, if the charge either originates or embeds itself in an insulator, a long-lived local space charge may result. Charge transfer, therefore, may result in either a temporary or a semipermanent effect.

[redacted] The free carriers produced during ionization respond to an applied electric field by producing a net drift current. This is precisely the mechanism by which a material conducts electricity. Therefore, ionization induces a transient increase in conductivity. An example of a detrimental effect to the operation of electronic equipment resulting from an increase in bulk conductivity occurs in a capacitor exposed to a weapon burst environment. The ability of a capacitor to retain, or restore, electrical charge is dependent upon the low conductivity of the dielectric, or insulating material, that is contained within the capacitor. In an ionizing environment the increase in bulk conductivity results in a decrease of stored charge in the capacitor.

[redacted] The ionization effect of excess minority carriers is a prime concern in many semiconductors and is usually the most important manifestation of TREE. Semiconductor devices, such as transistors and diodes, employ both positive and negative charge carriers, either of which may be in the minority with respect to concentration. The characteristics of many such devices depend strongly upon the instantaneous concentration of minority carriers in various regions of the device. Since ionizing radiation creates large (and equal) numbers of positive and negative charge carriers, the concentration of minority carriers in the device is temporarily enhanced by a large percentage, and the electrical operation of the device may be affected adversely. The most familiar example of this effect is the current flow across a reverse-biased PN junction, such as those that are found in a diode or the base-collector junction of a transistor (see Section VII, Chapter 9).

[redacted] When free carriers are created in insulating materials, and are trapped at impurity sites, many may not undergo recombination with their mates, which may be trapped elsewhere. In these cases, the material properties may be altered semipermanently, even though there is no net charge in the material. This ionization effect is known as charge trapping.

[redacted] Trapped charge can change the optical properties of materials (e.g., F centers in alkali halides, coloration of glasses). The trapped carriers may be released thermally, either at the irradiation temperature or by elevating the temperature. In either case the resultant creation of some free carriers is manifested by an increase in conductivity and sometimes by the emission of light.

[redacted] The chemical effects of ionization occur during the processes of trapping and recombination when sufficient energy is available to disrupt chemical bonds. At the completion of the ionization cycle (i.e., after recombination is complete), the material may return to electrical inactivity, but its chemical composition may be altered permanently. The resulting chemical changes may be manifested as permanent changes in physical and/or electrical properties of the material. The radiation dose required to cause such effects is larger than normally will be encountered; therefore, the effect will not be discussed further.

[redacted] Since ionization effects do not occur and/or recover in the same time period, the time domain for their occurrence and recovery must be considered. There are three categories of time [redacted] dependence – prompt, delayed, and long term.

[redacted] Prompt effects are those in which the width of the ionization pulse is longer than the times required for atoms or electrons within the material being exposed to make a specified amount of recovery. The magnitude of the effect is a function of the density of the positive and negative particles created during the ionization, which in turn is a function of the dose rate. Examples of prompt effects are charge transfer and prompt bulk-conductivity increases in insulating and semiconductor materials.

[redacted] Delayed effects are those in which the width of the ionization pulse is shorter than the times required for atoms or electrons within the material being exposed to make a specified amount of recovery. The initial response of the material or device is a function of dose, and its persistence is determined by the length of the specified recovery time. An example of this effect is delayed bulk conductivity of insulator materials. In this particular example the recovery times for the prompt and delayed effects are based on different mechanisms of carrier generation (ionization induced or thermal trapping) and, hence, they have very different time periods.

[redacted] Long-term effects are those which persist for periods longer than minutes. These effects can be, but are not necessarily, permanent. Recovery may be so slow that it takes days, months, or years for apparent complete recovery. Examples of long-term effects are some cases of trapped charge and chemical effects.

[redacted] An important point, emphasized here, is that a general class of materials or devices (plastics, transistors, etc.) could be both dose and dose-rate sensitive with respect to the ionization effects observed.

[redacted] It has been established that, with the exception of charge transfer, the magnitude of the ionization effects is primarily a function of the total concentration of thermalized charge carriers (electrons and holes). These carriers are generated at a rate proportional to the instantaneous ionization energy deposition and independent of the nature of the radiation producing that energy deposition. Therefore, it is appropriate to use units that quantify the energy deposition in the material of interest when describing the radiation field at the responding device. Such units include ergs/gram (material), rads (material), and calories/gram (material). Since these are descriptions of energy deposition in a given material, they are called units of dose. The time dependence of energy deposition can be specified by these same units per second, and are called dose rate.

[redacted] Unfortunately, the magnitude of charge transfer depends not only on the energy deposition but the spectrum of the secondary electrons. Therefore, quantitative evaluations of systems in which charge transfer represents a significant vulnerability mode must use a more complex characterization of the spectrum of the incident photons, together with a calculation of the photon interactions, to produce the spectrum of secondary electrons.

[redacted] In some materials, particularly insulators, the ionization effects are also a weak function of the microscopic concentration of the ionization around individual particle tracks. For example, neutron-induced ionization created by intensively ionizing recoil atom may be less effective in producing conductivity in an insulator than the same dose or dose rate imparted by lightly ionizing gamma rays. Units for describing this process include specific ionization (ratios of ionization to the minimum level of ionization at high velocities of a singly charged particle), and linear energy transfer (MeV/cm or MeV cm^2/gram). Fortunately, these effects are of second order importance for most TREE applications. A specification of dose rate and dose is adequate in the majority of applications.

[redacted] The gamma-ray field incident on a

[redacted]

system is frequently described by its exposure measure in roentgens. The roentgen is determined by specifying the energy deposition in a standard material (dry air under standard temperature and pressure conditions). For high energy gamma rays that interact primarily via the Compton process, exposure of almost any material to one roentgen of gamma rays produce (within 20%) approximately one rad of energy deposition in any material. This factor has enabled the users of these units to become somewhat careless, without serious consequence, so long as only high-energy photons are of interest. However, these relations do not carry over into photons of lower energies (200 kilovolts or less in medium atomic-number materials) and careful treatment of the units is required. One way of minimizing the chances of misinterpretation is to use units of calories/cm^2 with a defined spectrum for external exposure and units of cal/gram (material) for dose.

6-8 Displacement Effects [redacted]

[redacted] The displacement effects of prime concern to TREE are those generated in semiconductor materials. The lattice damage resulting from displacement degrades the electrical characteristics of semiconductor devices by increasing the number of trapping, scattering, and recombination centers. The effect of displacement in semiconductors is, therefore, threefold: (1) the trapping centers remove charge carriers from the electrical conduction process (reduces electrical current flow), (2) the additional scattering centers reduce the capability of the charge carriers to move through the semiconductor material (reduces charge-carrier mobility), and (3) the recombination centers reduce the time that the minority charge carriers are available for electrical conduction (reduces the lifetime of the minority-charge carriers). This last effect is most important for prediction of semiconductor device performance in radiation environments that cause displacement. The decrease in minority-carrier lifetime (τ) is predicted according to the relationship

$$\frac{1}{\tau_\varphi} = \frac{1}{\tau_0} + K\varphi ,$$

where

τ_φ = minority-carrier lifetime at fluence φ in seconds,

τ_0 = initial minority-carrier lifetime in seconds

K = lifetime damage constant, cm^2/(neutron · second)

φ = total fast-neutron fluence, neutrons/cm^2.

[redacted] Typical values for τ_o in device materials of interest are 10^{-8} to 10^{-4} seconds. The value of the lifetime damage constant, K, is dependent on the type of material, the type and amount of impurities in the material, the operating voltage applied to the material, the temperature, the energy spectrum of incident neutrons, and, because of defect annealing, the time after the nuclear radiation is incident on the material. A general value for silicon, the prime material used in transistors, diodes, and integrated circuits, is $K \approx 1 \times 10^{-6}$ cm^2/(n · sec).

[redacted] To illustrate the magnitude of displacement effects that occur in semiconductors compared to those that occur in other materials, a comparison of neutron fluences that will cause significant effects is made in the following paragraph. Interest is focused only on those property changes that affect the normal use of the materials being compared.

[redacted] Semiconductor lifetime can begin to show significant effects in devices at a fluence of 10^{11} n/cm^2 (Pu, fission)* and by 10^{16} n/cm^2

*Accurate neutron dosimetry requires that the foil used for making the neutron measurement and the energy spectrum of the neutrons be specified with the value measured. Therefore, in the example presented here, 10^{11} neutrons per square centimeter were detected with a plutonium foil and the energy spectrum of the neutrons was a nominal fission spectrum.

[redacted]

(Pu, fission) the lifetime in most semiconductor devices is so short that the device is no longer useful. Metals such as nickel and copper start to show effects in material strength at a fluence of 10^{18} n/cm^2 (Pu, fission). As a general rule, the electrical properties will not start to change in structural materials until the material properties change. Glasses and ceramics are much less susceptible to neutron damage than semiconductors, but they are more susceptible than metals. The point that is emphasized is that semiconductors are among the devices that are most susceptible to displacement effects.

[redacted] It is frequently desirable to express neutron effects data observed by different experimenters using different neutron-energy spectra in terms of an equivalence fluence unit in addition to the measured flux and fluence units. This permits easy comparison of damage levels obtained from different neutron test facilities. Since silicon is the material of most interest to displacement effects, the equivalence is usually based upon damage in silicon. The energy spectrum typically used as a standard for comparison is a hypothetical 1-MeV monoenergetic neutron source. The damage caused by the neutrons (of some known spectrum) is compared to the damage done by the neutron spectrum which is used as a standard. The neutron fluence of the standard which would cause the same damage in the given material as observed for the known spectrum is then specified as the damage equivalent fluence for that material. An example of this equivalence unit for 1-MeV neutrons standard spectrum and silicon material is: 10^{13} n/cm^2 (1-MeV damage equivalence in silicon). The procedures for obtaining a 1-MeV equivalent fluence for any known neutron spectrum are specified in the TREE Handbook (see bibliography).

6-9 Heating Effects [redacted]

[redacted] The radiation environment, especially the X-rays, produced by nuclear weapons can deposit considerable energy in electronic materials. The energy deposited is sufficient to heat some materials to such an extent as to cause partial melting, and it is sufficient to change electrical properties in other materials. These temperature transients may last from fractions of a second to minutes. If the energy is deposited in the material in a very short time (deposition time is typically 10^{-8} seconds for a nuclear weapon) an additional effect is observed; the material is heated very rapidly but does not have time to expand. The result is the instantaneous creation of a shock wave, or pressure pulse, which tends to compress the material. This compression wave starts at the point of energy absorption, typically close to the material's front surface upon which the incident energy impinges, and quickly propagates to the back surface. When it reaches the back surface, it is reflected, becomes a tension wave, and propagates toward the front surface. For energy deposition of sufficient magnitude delivered in a sufficiently short interval, the tension wave can be intense enough to exceed the strength of the material. Several consequences are possible.

(1) Portions of the material may be removed from the back surface – spallation (see Figure 6-5).

(2) Fragments of the material may separate from the front surface – blowoff.

(3) The material may separate between front and back surfaces – delamination.

(4) Agglomerates or layers of dissimilar materials bonded together will tend to separate at the interfaces – also called delamination.

(5) In brittle crystalline materials (e.g., Si or Ge), crystal fracture can occur.

Generally, effects of this nature are referred to as thermo~~chemical~~ mechanical shock effects. Obviously, the consequences of these effects can be catastrophic. An example important to transistors and inte-

[redacted]

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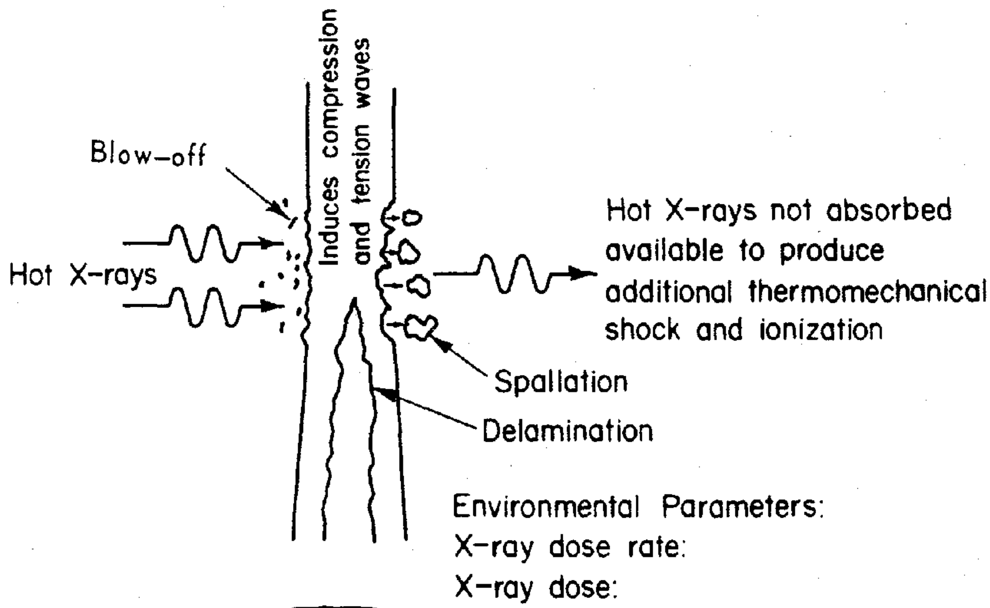

Figure 6-5. [redacted] Thermomechanical Shock Effects [redacted]

[redacted] grated circuits is the delamination of the electrical contacts to the semiconductor chip, resulting in complete loss of the device function. The thermomechanical-effect damage threshold is difficult to determine. It depends not only on the energy deposition and energy spectrum but also on the thickness of the materials, the compressibility, the expansion coefficient, and the dynamic strength of the materials. Thermomechanical effects on materials are discussed in more detail in Section VII of Chapter 9.

[redacted]

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